

Study of B_c^+ decays to the $K^+K^-\pi^+$ final state and evidence for the decay $B_c^+ \rightarrow \chi_{c0}\pi^+$

LHCb Collaboration

DOI:

[10.1103/PhysRevD.94.091102](https://doi.org/10.1103/PhysRevD.94.091102)

License:

Creative Commons: Attribution (CC BY)

Document Version

Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

LHCb Collaboration 2016, 'Study of B_c^+ decays to the $K^+K^-\pi^+$ final state and evidence for the decay $B_c^+ \rightarrow \chi_{c0}\pi^+$ ', *Physical Review D*, vol. 94, no. 9, 091102. <https://doi.org/10.1103/PhysRevD.94.091102>

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:

checked 15/1/19

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Study of B_c^+ decays to the $K^+K^-\pi^+$ final state and evidence for the decay $B_c^+ \rightarrow \chi_{c0}\pi^+$

R. Aaij *et al.**

(LHCb Collaboration)

(Received 21 July 2016; published 30 November 2016)

A study of $B_c^+ \rightarrow K^+K^-\pi^+$ decays is performed for the first time using data corresponding to an integrated luminosity of 3.0 fb^{-1} collected by the LHCb experiment in pp collisions at center-of-mass energies of 7 and 8 TeV. Evidence for the decay $B_c^+ \rightarrow \chi_{c0}(\rightarrow K^+K^-\pi^+)\pi^+$ is reported with a significance of 4.0 standard deviations, giving $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow \chi_{c0}\pi^+) = (9.8_{-3.0}^{+3.4}(\text{stat}) \pm 0.8(\text{syst})) \times 10^{-6}$. Here \mathcal{B} denotes a branching fraction while $\sigma(B_c^+)$ and $\sigma(B^+)$ are the production cross sections for B_c^+ and B^+ mesons. An indication of $\bar{b}c$ weak annihilation is found for the region $m(K^-\pi^+) < 1.834 \text{ GeV}/c^2$, with a significance of 2.4 standard deviations.

DOI: [10.1103/PhysRevD.94.091102](https://doi.org/10.1103/PhysRevD.94.091102)

Heavy-flavor physics involves studying the decays of hadrons containing at least one b or c valence quark, and offers the possibility of making precision measurements of Standard Model (SM) parameters and detecting effects of new physics. The B_c^+ meson ($\bar{b}c$), the only currently established hadron having two different heavy-flavor quarks, has the particularity of decaying weakly through either of its flavors.¹ In the SM, the B_c^+ decays with no charm and beauty particles in the final or intermediate states can proceed only via $\bar{b}c \rightarrow W^+ \rightarrow u\bar{q}$ ($q = d, s$) annihilation, with an amplitude proportional to the product of Cabibbo-Kobayashi-Maskawa matrix elements $V_{cb}^*V_{uq}$. Calculations predict branching fractions in the range 10^{-8} – 10^{-6} [1–3]. Any significant enhancement could indicate the presence of $\bar{b}c$ annihilations involving particles beyond the SM, such as a mediating charged Higgs boson (see, e.g., Ref. [4,5]).

Experimentally, the decays of B_c^+ mesons to three light charged hadrons provide a good way to study such processes. These decay modes have a large available phase space and can include other processes such as $B_c^+ \rightarrow D^0(\rightarrow K\pi)h^+$ ($h = \pi, K$) [6] mediated by $\bar{b} \rightarrow \bar{u}$ and $\bar{b} \rightarrow \bar{d}, \bar{s}$ transitions, $B_c^+ \rightarrow B_q^0(\rightarrow h_1^+h_2^-)h_3^+$ decays [7] mediated by $c \rightarrow q$ transitions, or charmonium modes $B_c^+ \rightarrow [c\bar{c}](\rightarrow h_1^+h_1^-)h_2^+$ [8] mediated by the $b \rightarrow c$ transition [9]. In this study, special consideration is given to decays leading to a $K^+K^-\pi^+$ final state in the region well below the D^0 mass, taken to be $m(K^-\pi^+) < 1.834 \text{ GeV}/c^2$, where, after removing possible contributions from

$([c\bar{c}], B_s^0) \rightarrow K^+K^-$, only the annihilation process remains. The other contributions listed above are also examined. The decay $B^+ \rightarrow \bar{D}^0(\rightarrow K^+K^-\pi^+)\pi^+$ is used as a normalization mode to derive

$$R_f \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow f), \quad (1)$$

where \mathcal{B} is the branching fraction, and $\sigma(B_c^+)$ and $\sigma(B^+)$ are the production cross sections of the B_c^+ and B^+ mesons. The quantity R_f is measured in the fiducial region $p_T(B) < 20 \text{ GeV}/c$ and $2.0 < y(B) < 4.5$, where p_T is the component of the momentum transverse to the proton beam and y denotes the rapidity. The data sample used corresponds to integrated luminosities of 1.0 and 2.0 fb^{-1} collected by the LHCb experiment at 7 and 8 TeV center-of-mass energies in pp collisions, respectively. Since the kinematics of B meson production is very similar at the two energies, the ratio $\frac{\sigma(B_c^+)}{\sigma(B^+)}$ is assumed to be the same for all the measurements discussed in this paper.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [10,11]. The detector allows the reconstruction of both charged and neutral particles. For this analysis, the ring-imaging Cherenkov detectors [12], distinguishing pions, kaons and protons, are particularly important. Simulated events are produced using the software described in Refs. [13–19].

The $B_c^+ \rightarrow K^+K^-\pi^+$ decay candidates are reconstructed applying the same selection procedure as in Ref. [20]. A similar multivariate analysis is implemented, using a boosted decision tree (BDT) classifier [21]. Particle identification (PID) requirements are then applied to reduce the combinatorial background and suppress the cross feed from pions misidentified as kaons. The BDT and PID requirements are optimized to maximize the sensitivity to small event yields.

*Full author list given at the end of the article.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

¹Charge conjugation is implied throughout the paper.

The B_c^+ signal yield is determined from a simultaneous fit in three bins of the BDT output \mathcal{O}_{BDT} , $0.04 < \mathcal{O}_{\text{BDT}} < 0.12$, $0.12 < \mathcal{O}_{\text{BDT}} < 0.18$ and $\mathcal{O}_{\text{BDT}} > 0.18$, each having similar expected yield but different levels of background [20]. The normalization channel $B^+ \rightarrow \bar{D}^0(\rightarrow K^+K^-)\pi^+$ uses the same BDT classifier, with tighter PID requirements to suppress the abundant background from $B^+ \rightarrow K^+\pi^-\pi^+$ decays. Its yield is determined requiring $\mathcal{O}_{\text{BDT}} > 0.04$, and demanding $1.834 < m(K^+K^-) < 1.894 \text{ GeV}/c^2$ to remove charmless $B^+ \rightarrow K^+K^-\pi^+$ candidates.

Signal and background yields are obtained from extended unbinned maximum likelihood fits to the distribution of the invariant mass of the $K^+K^-\pi^+$ combinations. The $B_c^+ \rightarrow K^+K^-\pi^+$ and $B^+ \rightarrow K^+K^-\pi^+$ signals are each modelled by the sum of two Crystal Ball functions [22] with a common mean. For $B_c^+ \rightarrow K^+K^-\pi^+$ all the shape parameters and the relative yields in each bin of \mathcal{O}_{BDT} are fixed to the values obtained in the simulation, while for $B^+ \rightarrow K^+K^-\pi^+$ the mean and the core width are allowed to vary freely in the fit. A Fermi-Dirac function is used to model a possible partially reconstructed component from decays with $K^+K^-\pi^+\pi^0$ final states where the neutral pion is not reconstructed, resulting in a $K^+K^-\pi^+$ invariant mass below the nominal B_c^+ or B^+ mass. All shape parameters of these background components are fixed to the values obtained from simulation. The combinatorial background is modeled by an exponential function. Figure 1 shows the result of the fit to determine the yield of the $B^+ \rightarrow \bar{D}^0(\rightarrow K^+K^-)\pi^+$ channel, $N_u = 8577 \pm 109$.

In the B_c^+ region $6.0 < m(K^+K^-\pi^+) < 6.5 \text{ GeV}/c^2$, the signals are fitted separately for regions of the phase space corresponding to the different expected contributions: the annihilation region ($m(K^-\pi^+) < 1.834 \text{ GeV}/c^2$), the $D^0 \rightarrow K^-\pi^+$ region ($1.834 < m(K^-\pi^+) < 1.894 \text{ GeV}/c^2$)

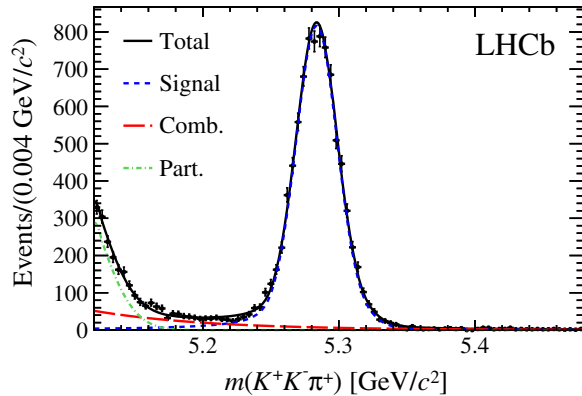


FIG. 1. Fit to the $K^+K^-\pi^+$ invariant mass for the B^+ candidates, with $1.834 < m(K^+K^-) < 1.894 \text{ GeV}/c^2$. The contributions from the signal $B^+ \rightarrow \bar{D}^0(\rightarrow K^+K^-)\pi^+$, combinatorial background (Comb.) and partially reconstructed background (Part.) obtained from the fit are shown.

and the $B_s^0 \rightarrow K^-K^+$ region ($5.3 < m(K^+K^-) < 5.4 \text{ GeV}/c^2$). For the first two regions, the ranges $3.38 < m(K^+K^-) < 3.46 \text{ GeV}/c^2$ and $5.2 < m(K^+K^-) < 5.5 \text{ GeV}/c^2$ are vetoed to remove contributions from χ_{c0} (as discussed below) and $B_{(s)}^0 \rightarrow h_1^+h_2^-$ decays. A possible signal is seen in the annihilation region, as shown in Fig. 2. The corresponding yield is $N_c = 20.8_{-9.9}^{+11.4}$, with a statistical significance of 2.5 standard deviations (σ), inferred from the difference in the logarithm of the likelihood for fits with and without the signal component.

The distribution of events in the $m^2(K^-\pi^+)$ vs $m^2(K^+K^-)$ plane, for the B_c^+ signal region $6.2 < m(K^+K^-\pi^+) < 6.35 \text{ GeV}/c^2$, is shown in Fig. 3. A concentration of events is observed around $m^2(K^+K^-) \sim 11 \text{ GeV}^2/c^4$. A one-dimensional projection of $m(K^+K^-)$ shows clustering near $3.41 \text{ GeV}/c^2$, close to the mass of the charmonium state χ_{c0} . Among all the charmonia, χ_{c0} has the highest branching fraction into the K^+K^- final state [23]. The accumulation of events near

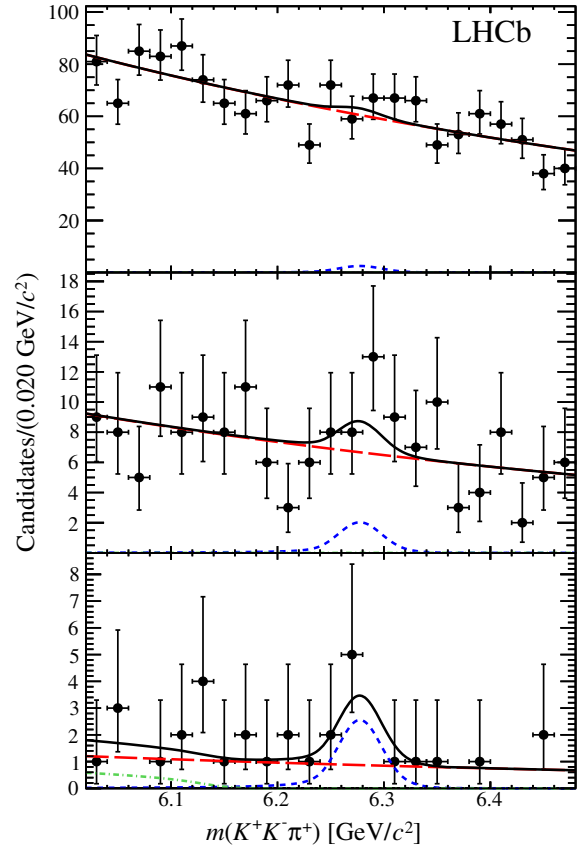


FIG. 2. Projection of the fit to the $K^+K^-\pi^+$ invariant mass in the B_c^+ region, in the bins of BDT output used in the analysis: (top) $0.04 < \mathcal{O}_{\text{BDT}} < 0.12$, (middle) $0.12 < \mathcal{O}_{\text{BDT}} < 0.18$ and (bottom) $\mathcal{O}_{\text{BDT}} > 0.18$, for $m(K^-\pi^+) < 1.834 \text{ GeV}/c^2$, including the vetoes in $m(K^+K^-)$ (see text). Apart from the signal type, which is given by $B_c^+ \rightarrow K^+K^-\pi^+$, the contributions are indicated according to the same scheme as in Fig. 1.

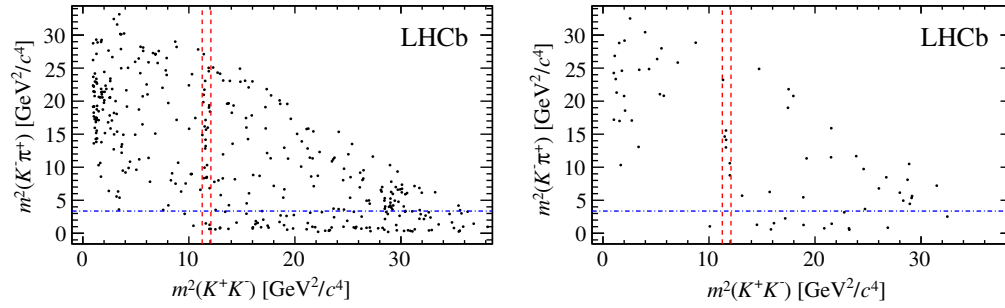


FIG. 3. Distribution of events for the signal region $6.2 < m(K^+K^-\pi^+) < 6.35 \text{ GeV}/c^2$ in the $m^2(K^-\pi^+)$ vs $m^2(K^+K^-)$ plane for (left) $\mathcal{O}_{\text{BDT}} > 0.12$ and (right) $\mathcal{O}_{\text{BDT}} > 0.18$. The vertical red dashed lines represent a band of width $\pm 60 \text{ MeV}/c^2$ around the χ_{c0} mass. The horizontal blue dot-dashed line indicates the upper bound of the annihilation region at $m(K^-\pi^+) = 1.834 \text{ GeV}/c^2$, representing 17% of the available phase space area.

$m^2(K^+K^-) \sim 29 \text{ GeV}^2/c^4$ for the loose \mathcal{O}_{BDT} cut appears to be mainly caused by $B_s^0 \rightarrow K^+K^-$ decays combined with random pions since no peak is seen in $m(K^+K^-\pi^+)$ at the B_c^+ mass [9].

To determine the $B_c^+ \rightarrow \chi_{c0}(\rightarrow K^+K^-)\pi^+$ signal yield, the two-dimensional $m(K^+K^-\pi^+)$ vs $m(K^+K^-)$ distributions are fitted simultaneously for each of the three BDT bins. The $m(K^+K^-\pi^+)$ distribution is modeled in the same

way as described above. The $m(K^+K^-)$ distribution is fitted in the range $3.20 < m(K^+K^-) < 3.55 \text{ GeV}/c^2$. The $\chi_{c0} \rightarrow K^+K^-$ shape is modeled by a Breit-Wigner function, with mean and width fixed to their known values [23], convolved with a Gaussian resolution function, while a first-order polynomial is used to represent the K^+K^- background. Figure 4 shows the projections of the fit result. The yield obtained is $N_{\chi_{c0}} = 20.8^{+7.2}_{-6.4}$, with a

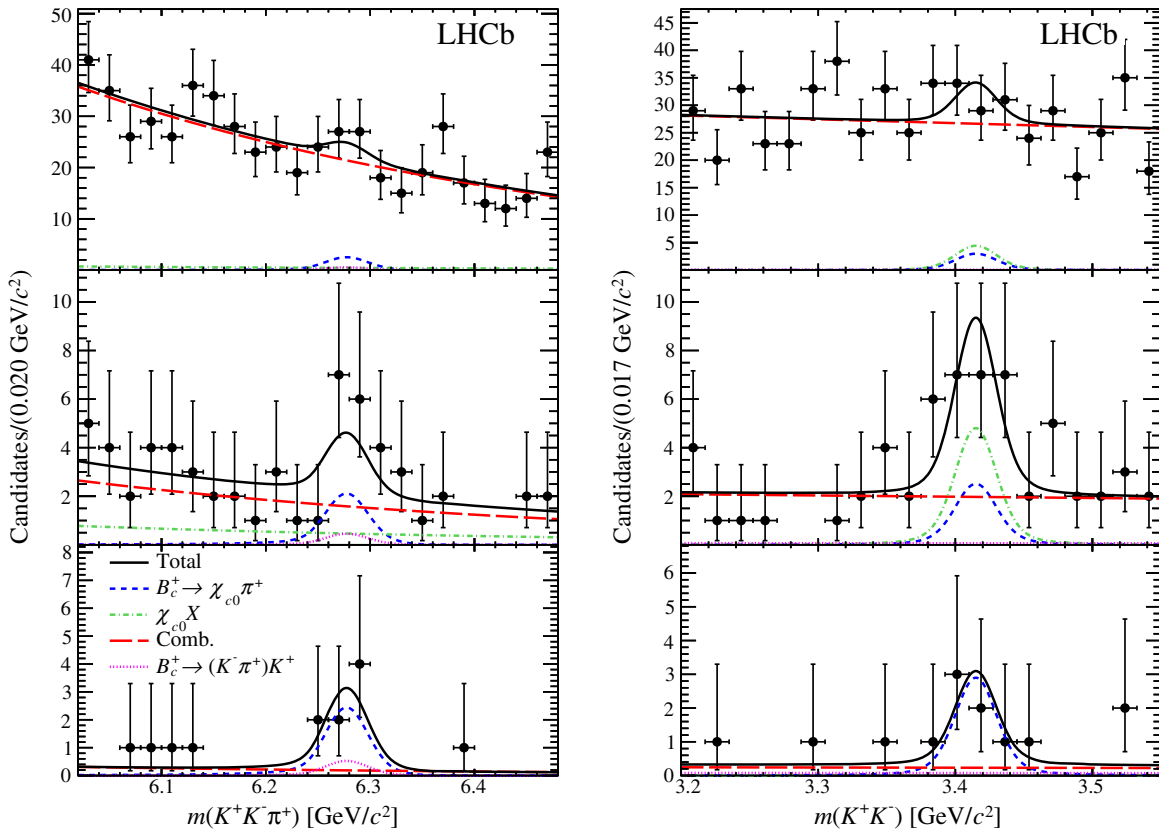


FIG. 4. Fit projections to the (left) $K^+K^-\pi^+$ and (right) K^+K^- invariant masses, in the bins of BDT output (top) $0.04 < \mathcal{O}_{\text{BDT}} < 0.12$, (middle) $0.12 < \mathcal{O}_{\text{BDT}} < 0.18$ and (bottom) $\mathcal{O}_{\text{BDT}} > 0.18$, for the extraction of the $B_c^+ \rightarrow \chi_{c0}(\rightarrow K^+K^-)\pi^+$ signal. The contributions from the $B_c^+ \rightarrow \chi_{c0}(\rightarrow K^+K^-)\pi^+$ signal, combinatorial background (Comb.), possible pollution from the annihilation region $B_c^+ \rightarrow (K^-\pi^+)K^+$, and combinations of $\chi_{c0} \rightarrow K^+K^-$ with a random track X are shown.

statistical significance of 4.1σ . The fits for the D^0 and B_s^0 regions, where no signal is observed, can be found at Ref. [9].

For each region of phase space considered, the efficiencies for the signals, ϵ_c , and normalization channel, ϵ_u , are inferred from simulated samples and are corrected using data-driven methods as described in Ref. [20]. They include the effects of reconstruction, selection and detector acceptance. An efficiency map defined in the $m^2(K^-\pi^+)$ vs $m^2(K^+K^-)$ plane is computed. Because of limited statistics, the distribution of the signal events in the annihilation region is not well known. Therefore, the efficiency for the annihilation region is estimated in two ways: first, by taking the simple average efficiency from the map for $m(K^-\pi^+) < 1.834 \text{ GeV}/c^2$ and, alternatively, by taking the efficiency weighted according to the sparse distribution of candidates in data in the $m^2(K^-\pi^+)$ vs $m^2(K^+K^-)$ plane. The average of the two values is taken as the efficiency and the difference is treated as a systematic uncertainty (labeled as “event distribution” in Table I). A correction accounting for the vetoed $m(K^+K^-)$ regions described above is included. In the calculation of the observable R_f the efficiency ratio ϵ_u/ϵ_c is required. The values obtained are 1.698 ± 0.015 for the annihilation region and 1.241 ± 0.012 for the $B_c^+ \rightarrow \chi_{c0}(K^+K^-)\pi^+$ mode. The uncertainties are due to the limited sizes of the simulated samples. The differences between the B^+ and B_c^+ efficiencies are caused by the different lifetimes and masses of the two mesons.

The measured quantities are determined as

$$R_{\text{an},KK\pi} = \frac{N_c}{N_u} \times \frac{\epsilon_u}{\epsilon_c(\text{an}, KK\pi)} \times \mathcal{B}(B^\pm \rightarrow D^0\pi^\pm) \times \mathcal{B}(D^0 \rightarrow K^+K^-)$$

for the annihilation region and

TABLE I. Relative systematic uncertainties (in %) of the measurements of $R_{\text{an},KK\pi}$ and $R_{\chi_{c0}\pi}$.

Source	$R_{\text{an},KK\pi}$	$R_{\chi_{c0}\pi}$
Normalization yield	1.3	1.3
Event distribution	1.6	...
Fit model	2.4	2.3
BDT shape	5.0	2.9
PID	1.0	1.0
Simulation	0.8	0.8
Detector acceptance	0.4	0.3
B_c^+ lifetime	2.0	2.0
Hardware trigger	1.5	1.4
Fiducial cut	0.1	0.1
Branching fractions	3.6	6.2
Total	7.5	7.8

$$R_{\chi_{c0}\pi} = \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow \chi_{c0}\pi^+) = \frac{N_{\chi_{c0}}}{N_u} \times \frac{\epsilon_u}{\epsilon_c(\chi_{c0})} \times \frac{\mathcal{B}(B^\pm \rightarrow D^0\pi^\pm) \times \mathcal{B}(D^0 \rightarrow K^+K^-)}{\mathcal{B}(\chi_{c0} \rightarrow K^+K^-)}$$

for the $B_c^+ \rightarrow \chi_{c0}\pi^+$ decay, where ϵ_x are the efficiencies and N_x are the yields obtained from the fits.

Systematic uncertainties are associated with the yield ratios, the efficiency ratios and the branching fractions $\mathcal{B}(B^+ \rightarrow \bar{D}^0\pi^+) = (4.81 \pm 0.15) \times 10^{-3}$, $\mathcal{B}(D^0 \rightarrow K^+K^-) = (4.01 \pm 0.07) \times 10^{-3}$ and $\mathcal{B}(\chi_{c0} \rightarrow K^+K^-) = (5.91 \pm 0.32) \times 10^{-3}$ [23]. Table I summarizes the uncertainties. The yields are affected by the uncertainties on the fit functions and parameters, and by the variation of the yield fractions in the BDT output bins, due to the uncertainty on the BDT output distribution. The uncertainties on the efficiency ratios reflect the PID calibration, the limited sizes of the simulated samples, the effect of the detector acceptance, the B_c^+ lifetime $0.507 \pm 0.009 \text{ ps}$ [24], and the trigger and fiducial cut corrections.

The results obtained are $R_{\text{an},KK\pi} = (8.0_{-3.8}^{+4.4}(\text{stat}) \pm 0.6(\text{syst})) \times 10^{-8}$ and $R_{\chi_{c0}\pi} = (9.8_{-3.0}^{+3.4}(\text{stat}) \pm 0.8(\text{syst})) \times 10^{-6}$. Accounting for the systematic uncertainties related to the signal extraction, the significances of these measurements are 2.4σ and 4.0σ , respectively. For the annihilation region, a 90(95)% confidence level (C.L.) upper limit, $R_{\text{an},KK\pi} < 15(17) \times 10^{-8}$, is estimated by making a scan of $R_{\text{an},KK\pi}$, comparing profile likelihood ratios for the “signal + background” and “background-only” hypotheses [9,25].

For the modes $B_c^+ \rightarrow B_s^0(\rightarrow K^+K^-)\pi^+$ and $B_c^+ \rightarrow D^0(\rightarrow K^-\pi^+)K^+$, no significant deviation from the background-only hypothesis is observed. Using $\mathcal{B}(B_s^0 \rightarrow K^+K^-) = (2.50 \pm 0.17) \times 10^{-5}$ and $\mathcal{B}(D^0 \rightarrow K^-\pi^+) = (3.93 \pm 0.04)\%$ [23], the following 90(95)% C.L. upper limits are obtained: $R_{B_s^0\pi} \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow B_s^0\pi^+) < 4.5(5.4) \times 10^{-3}$ and $R_{D^0K} \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow D^0K^+) < 1.3(1.6) \times 10^{-6}$. The first limit is consistent with the result of Ref. [26], which gives $R_{B_s^0\pi} = (6.2 \pm 1.0) \times 10^{-4}$, using $\sigma(B_s^0)/\sigma(B^+) = 0.258 \pm 0.016$ [27,28].

In summary, a study of B_c^+ meson decays to the $K^+K^-\pi^+$ final state has been performed in the fiducial region $p_T(B) < 20 \text{ GeV}/c$ and $2.0 < y(B) < 4.5$. Evidence for the decay $B_c^+ \rightarrow \chi_{c0}\pi^+$ is found at 4.0σ significance. This result can be compared to the measurement involving another charmonium mode, $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+) = (7.0 \pm 0.3) \times 10^{-6}$, obtained from Refs. [23,29].

A indication of $\bar{b}c$ weak annihilation with a significance of 2.4σ is reported in the region $m(K^-\pi^+) < 1.834 \text{ GeV}/c^2$. The branching fraction of $B_c^+ \rightarrow \bar{K}^{*0}(892)K^+$ has been recently predicted to be $(10.0_{-3.4}^{+1.8}) \times 10^{-7}$ [3]. The contribution of the mode

$B_c^+ \rightarrow \bar{K}^{*0}(892)(\rightarrow K^-\pi^+)K^+$ to $R_{\text{an},KK\pi}$ could be prominent, for which an estimate is made as follows. Using the predictions listed in Ref. [30] for $\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)$, which span the range $[0.34, 2.9] \times 10^{-3}$, and the value of $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)$ based on Ref. [29] quoted above, $\frac{\sigma(B_c^+)}{\sigma(B^+)} \sim [0.23, 2.1]\%$ is obtained. Combined with the prediction of Ref. [3], a value of $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \rightarrow \bar{K}^{*0}(892)(\rightarrow K^-\pi^+)K^+) \sim [0.1, 1.7] \times 10^{-8}$ is obtained, including the theoretical uncertainties and the $\bar{K}^{*0}(892) \rightarrow K^-\pi^+$ branching fraction. This estimate is lower than the $R_{\text{an},KK\pi}$ measurement. The statistical uncertainty, however, is at present too large to make a definite statement. The data being accumulated in the current run of the LHC will allow LHCb to clarify whether the weak annihilation process of B_c^+ meson decays involves significant contributions from heavier $K^-\pi^+$ states, or is enhanced by other sources.

ACKNOWLEDGMENTS

We express our gratitude to our colleagues in the CERN (European Laboratory for Particle Physics) accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb

institutes. We acknowledge support from CERN and from the following national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); FOM and NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FANO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany), EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union), Conseil Général de Haute-Savoie, Labex ENIGMASS and OCEVU, Région Auvergne (France), RFBR and Yandex LLC (Russia), GVA, XuntaGal and GENCAT (Spain), Herchel Smith Fund, The Royal Society, Royal Commission for the Exhibition of 1851 and the Leverhulme Trust (United Kingdom).

-
- [1] S. Descotes-Genon, J. He, E. Kou, and P. Robbe, Non-leptonic charmless B_c decays and their search at LHCb, *Phys. Rev. D* **80**, 114031 (2009).
 - [2] X. Liu, Z.-J. Xiao, and C.-D. Lu, Pure annihilation type $B_c \rightarrow M_2 M_3$ decays in the perturbative QCD approach, *Phys. Rev. D* **81**, 014022 (2010).
 - [3] Z.-J. Xiao and X. Liu, The two-body hadronic decays of B_c meson in the perturbative QCD approach: A short review, *Chin. Sci. Bull.* **59**, 3748 (2014).
 - [4] W.-S. Hou, Enhanced charged Higgs boson effects in $B^- \rightarrow \tau \bar{\nu}$, $\mu \bar{\nu}$ and $b \rightarrow \tau \bar{\nu} + X$, *Phys. Rev. D* **48**, 2342 (1993).
 - [5] S. Kanemura, M. Kikuchi, and K. Yagyu, Fingerprinting the extended Higgs sector using one-loop corrected Higgs boson couplings and future precision measurements, *Nucl. Phys.* **B896**, 80 (2015).
 - [6] Z. Rui, Z.-T. Zou, and C.-D. Lu, The two-body $B_c \rightarrow D_{(s)}^{(*)} P$, $D_{(s)}^{(*)} V$ decays in the perturbative QCD approach, *Phys. Rev. D* **86**, 074008 (2012).
 - [7] J. Sun, Y. Yang, Q. Chang, and G. Lu, Phenomenological study of the $B_c \rightarrow BP$, BV decays with perturbative QCD approach, *Phys. Rev. D* **89**, 114019 (2014).
 - [8] C.-F. Qiao, P. Sun, D. Yang, and R.-L. Zhu, B_c exclusive decays to charmonium and a light meson at next-to-leading order accuracy, *Phys. Rev. D* **89**, 034008 (2014).
 - [9] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevD.94.091102> for Feynman diagrams of the processes intervening in this study, simultaneous mass fits of unobserved processes reported in the paper, and p-value scans of the measured observables.
 - [10] A. A. Alves, Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, *J. Instrum.* **3**, S08005 (2008).
 - [11] R. Aaij *et al.* (LHCb Collaboration), LHCb detector performance, *Int. J. Mod. Phys. A* **30**, 1530022 (2015).
 - [12] M. Adinolfi *et al.*, Performance of the LHCb RICH detector at the LHC, *Eur. Phys. J. C* **73**, 2431 (2013).
 - [13] T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026; A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008).
 - [14] I. Belyaev *et al.*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, *J. Phys. Conf. Ser.* **331**, 032047 (2011).
 - [15] D. J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
 - [16] J. Allison *et al.* (Geant4 Collaboration), Geant4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006); S. Agostinelli *et al.* (Geant4 Collaboration), Geant4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).

- [17] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranza, M. Pappagallo, and P. Robbe, The LHCb simulation application, Gauss: Design, evolution and experience, *J. Phys. Conf. Ser.* **331**, 032023 (2011).
- [18] C.-H. Chang, C. Driouichi, P. Eerola, and X.-G. Wu, BCVEGPY: An event generator for hadronic production of the B_c meson, *Comput. Phys. Commun.* **159**, 192 (2004).
- [19] C.-H. Chang, J.-X. Wang, and X.-G. Wu, BCVEGPY2.0: A upgrade version of the generator BCVEGPY with an addendum about hadroproduction of the P -wave B_c states, *Comput. Phys. Commun.* **174**, 241 (2006).
- [20] R. Aaij *et al.* (LHCb Collaboration), Search for B_c decays to the $p\bar{p}\pi$ final state, *Phys. Lett. B* **759**, 313 (2016).
- [21] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and Regression Trees* (Wadsworth International Group, Belmont, 1984).
- [22] T. Skwarnicki, Ph.D. thesis, Institute of Nuclear Physics (Report No. DESY-F31-86-02, 1986).
- [23] K. A. Olive *et al.* (Particle Data Group), Review of particle physics, *Chin. Phys. C* **38**, 090001 (2014), and 2015 update.
- [24] Y. Amhis *et al.* (Heavy Flavor Averaging Group), Averages of b -hadron, c -hadron, and τ -lepton properties as of summer 2014, [arXiv:1412.7515](https://arxiv.org/abs/1412.7515), <http://www.slac.stanford.edu/xorg/hfag/>.
- [25] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* **71**, 1554 (2011).
- [26] R. Aaij *et al.* (LHCb Collaboration), Observation of the Decay $B_c^+ \rightarrow B_s^0 \pi^+$, *Phys. Rev. Lett.* **111** (2013) 181801.
- [27] R. Aaij *et al.* (LHCb Collaboration), Measurement of b hadron production fractions in 7 TeV pp collisions, *Phys. Rev. D* **85**, 032008 (2012).
- [28] R. Aaij *et al.* (LHCb Collaboration), Measurement of the fragmentation fraction ratio f_s/f_d and its dependence on B meson kinematics, *J. High Energy Phys.* **04** (2013) 001.
- [29] R. Aaij *et al.* (LHCb Collaboration), Measurement of B_c^+ production at $\sqrt{s} = 8$ TeV, *Phys. Rev. Lett.* **114**, 132001 (2015).
- [30] Z. Rui and Z.-T. Zhou, S-wave ground state charmonium decays of B_c mesons in the perturbative QCD, *Phys. Rev. D* **90**, 114030 (2014), and references therein.

R. Aaij,⁴⁰ B. Adeva,³⁹ M. Adinolfi,⁴⁸ Z. Ajaltouni,⁵ S. Akar,⁶ J. Albrecht,¹⁰ F. Alessio,⁴⁰ M. Alexander,⁵³ S. Ali,⁴³ G. Alkhazov,³¹ P. Alvarez Cartelle,⁵⁵ A. A. Alves Jr.,⁵⁹ S. Amato,²³ S. Amerio,⁷ Y. Amhis,⁷ L. An,⁴¹ L. Anderlini,¹⁸ G. Andreassi,⁴¹ M. Andreotti,^{17,a} J. E. Andrews,⁶⁰ R. B. Appleby,⁵⁶ F. Archilli,⁴³ P. d'Argent,¹² J. Arnau Romeu,⁶ A. Artamonov,³⁷ M. Artuso,⁶¹ E. Aslanides,⁶ G. Auriemma,²⁶ M. Baalouch,⁵ I. Babuschkin,⁵⁶ S. Bachmann,¹² J. J. Back,⁵⁰ A. Badalov,³⁸ C. Baesso,⁶² W. Baldini,¹⁷ R. J. Barlow,⁵⁶ C. Barschel,⁴⁰ S. Barsuk,⁷ W. Barter,⁴⁰ M. Baszczyk,²⁷ V. Batozskaya,²⁹ B. Batsukh,⁶¹ V. Battista,⁴¹ A. Bay,⁴¹ L. Beaucourt,⁴ J. Beddow,⁵³ F. Bedeschi,²⁴ I. Bediaga,¹ L. J. Bel,⁴³ V. Bellee,⁴¹ N. Belloli,^{21,b} K. Belous,³⁷ I. Belyaev,³² E. Ben-Haim,⁸ G. Bencivenni,¹⁹ S. Benson,⁴³ J. Benton,⁴⁸ A. Bereznoi,³³ R. Bernet,⁴² A. Bertolin,²³ F. Betti,¹⁵ M.-O. Bettler,⁴⁰ M. van Beuzekom,⁴³ I. Bezshyiko,⁴² S. Bifani,⁴⁷ P. Billoir,⁸ T. Bird,⁵⁶ A. Birnkraut,¹⁰ A. Bitadze,⁵⁶ A. Bizzeti,^{18,c} T. Blake,⁵⁰ F. Blanc,⁴¹ J. Blouw,¹¹ S. Blusk,⁶¹ V. Bocci,²⁶ T. Boettcher,⁵⁸ A. Bondar,^{36,d} N. Bondar,^{31,40} W. Bonivento,¹⁶ A. Borgheresi,^{21,b} S. Borghi,⁵⁶ M. Borisyak,³⁵ M. Borsato,³⁹ F. Bossu,⁷ M. Boubdir,⁹ T. J. V. Bowcock,⁵⁴ E. Bowen,⁴² C. Bozzi,^{17,40} S. Braun,¹² M. Britsch,¹² T. Britton,⁶¹ J. Brodzicka,⁵⁶ E. Buchanan,⁴⁸ C. Burr,⁵⁶ A. Bursche,² J. Buytaert,⁴⁰ S. Cadceddu,¹⁶ R. Calabrese,^{17,a} M. Calvi,^{21,b} M. Calvo Gomez,^{38,e} A. Camboni,³⁸ P. Campana,¹⁹ D. Campora Perez,⁴⁰ D. H. Campora Perez,⁴⁰ L. Capriotti,⁵⁶ A. Carbone,^{15,f} G. Carboni,^{25,g} R. Cardinale,^{20,h} A. Cardini,¹⁶ P. Carniti,^{21,b} L. Carson,⁵² K. Carvalho Akiba,² G. Casse,⁵⁴ L. Cassina,^{21,b} L. Castillo Garcia,⁴¹ M. Cattaneo,⁴⁰ Ch. Cauet,¹⁰ G. Cavallero,²⁰ R. Cenci,^{24,i} M. Charles,⁸ Ph. Charpentier,⁴⁰ G. Chatzikonstantinidis,⁴⁷ M. Chefdeville,⁴ S. Chen,⁵⁶ S.-F. Cheung,⁵⁷ V. Chobanova,³⁹ M. Chrzasczcz,^{42,27} X. Cid Vidal,³⁹ G. Ciezarek,⁴³ P. E. L. Clarke,⁵² M. Clemencic,⁴⁰ H. V. Cliff,⁴⁹ J. Closier,⁴⁰ V. Coco,⁵⁹ J. Cogan,⁶ E. Cogneras,⁵ V. Cogoni,^{16,40,j} L. Cojocariu,³⁰ G. Collazuol,^{23,k} P. Collins,⁴⁰ A. Comerma-Montells,¹² A. Contu,⁴⁰ A. Cook,⁴⁸ S. Coquereau,³⁸ G. Corti,⁴⁰ M. Corvo,^{17,a} C. M. Costa Sobral,⁵⁰ B. Couturier,⁴⁰ G. A. Cowan,⁵² D. C. Craik,⁵² A. Crocombe,⁵⁰ M. Cruz Torres,⁶² S. Cunliffe,⁵⁵ R. Currie,⁵⁵ C. D'Ambrosio,⁴⁰ E. Dall'Occo,⁴³ J. Dalseno,⁴⁸ P. N. Y. David,⁴³ A. Davis,⁵⁹ O. De Aguiar Francisco,² K. De Bruyn,⁶ S. De Capua,⁵⁶ M. De Cian,¹² J. M. De Miranda,¹ L. De Paula,² M. De Serio,^{14,l} P. De Simone,¹⁹ C.-T. Dean,⁵³ D. Decamp,⁴ M. Deckenhoff,¹⁰ L. Del Buono,⁸ M. Demmer,¹⁰ D. Derkach,³⁵ O. Deschamps,⁵ F. Dettori,⁴⁰ B. Dey,²² A. Di Canto,⁴⁰ H. Dijkstra,⁴⁰ F. Dordei,⁴⁰ M. Dorigo,⁴¹ A. Dosil Suárez,³⁹ A. Dovbnya,⁴⁵ K. Dreimanis,⁵⁴ L. Dufour,⁴³ G. Dujany,⁵⁶ K. Dungs,⁴⁰ P. Durante,⁴⁰ R. Dzhelezhadine,³⁷ A. Dziurda,⁴⁰ A. Dzyuba,³¹ N. Deléage,⁴ S. Easo,⁵¹ M. Ebert,⁵² U. Egede,⁵⁵ V. Egorychev,³² S. Eidelman,^{36,d} S. Eisenhardt,⁵² U. Eitschberger,¹⁰ R. Ekelhof,¹⁰ L. Eklund,⁵³ Ch. Elsasser,⁴² S. Ely,⁶¹ S. Esen,¹² H. M. Evans,⁴⁹ T. Evans,⁵⁷ A. Falabella,¹⁵ N. Farley,⁴⁷ S. Farry,⁵⁴ R. Fay,⁵⁴ D. Fazzini,^{21,b} D. Ferguson,⁵² V. Fernandez Albor,³⁹ A. Fernandez Prieto,³⁹ F. Ferrari,^{15,40} F. Ferreira Rodrigues,¹ M. Ferro-Luzzi,⁴⁰ S. Filippov,³⁴ R. A. Fini,¹⁴ M. Fiore,^{17,a} M. Fiorini,^{17,a} M. Firlej,²⁸ C. Fitzpatrick,⁴¹ T. Fiutowski,²⁸ F. Fleuret,^{7,m} K. Fohl,⁴⁰ M. Fontana,¹⁶ F. Fontanelli,^{20,h} D. C. Forshaw,⁶¹ R. Forty,⁴⁰

- V. Franco Lima,⁵⁴ M. Frank,⁴⁰ C. Frei,⁴⁰ J. Fu,^{22,n} E. Furfaro,^{25,g} C. Färber,⁴⁰ A. Gallas Torreira,³⁹ D. Galli,^{15,f} S. Gallorini,²³ S. Gambetta,⁵² M. Gandelman,² P. Gandini,⁵⁷ Y. Gao,³ L. M. Garcia Martin,⁶⁸ J. García Pardiñas,³⁹ J. Garra Tico,⁴⁹ L. Garrido,³⁸ P. J. Garsed,⁴⁹ D. Gascon,³⁸ C. Gaspar,⁴⁰ L. Gavardi,¹⁰ G. Gazzoni,⁵ D. Gerick,¹² E. Gersabeck,¹² M. Gersabeck,⁵⁶ T. Gershon,⁵⁰ Ph. Ghez,⁴ S. Gianì,⁴¹ V. Gibson,⁴⁹ O. G. Girard,⁴¹ L. Giubega,³⁰ K. Gizdov,⁵² V. V. Gligorov,⁸ D. Golubkov,³² A. Golutvin,^{55,40} A. Gomes,^{1,o} I. V. Gorelov,³³ C. Gotti,^{21,b} M. Grabalosa Gándara,⁵ R. Graciani Diaz,³⁸ L. A. Granado Cardoso,⁴⁰ E. Graugés,³⁸ E. Graverini,⁴² G. Graziani,¹⁸ A. Grecu,³⁰ P. Griffith,⁴⁷ L. Grillo,^{21,b} B. R. Gruberg Cazon,⁵⁷ O. Grünberg,⁶⁶ E. Gushchin,³⁴ Yu. Guz,³⁷ T. Gys,⁴⁰ C. Göbel,⁶² T. Hadavizadeh,⁵⁷ C. Hadjivasilou,⁵ G. Haefeli,⁴¹ C. Haen,⁴⁰ S. C. Haines,⁴⁹ S. Hall,⁵⁵ B. Hamilton,⁶⁰ X. Han,¹² S. Hansmann-Menzemer,¹² N. Harnew,⁵⁷ S. T. Harnew,⁴⁸ J. Harrison,⁵⁶ M. Hatch,⁴⁰ J. He,⁶³ T. Head,⁴¹ A. Heister,⁹ K. Hennessy,⁵⁴ P. Henrard,⁵ L. Henry,⁸ J. A. Hernando Morata,³⁹ E. van Herwijnen,⁴⁰ M. Heß,⁶⁶ A. Hicheur,² D. Hill,⁵⁷ C. Hombach,⁵⁶ H. Hopchev,⁴¹ W. Hulsbergen,⁴³ T. Humair,⁵⁵ M. Hushchyn,³⁵ N. Hussain,⁵⁷ D. Hutchcroft,⁵⁴ M. Idzik,²⁸ P. Ilten,⁵⁸ R. Jacobsson,⁴⁰ A. Jaeger,¹² J. Jalocha,⁵⁷ E. Jans,⁴³ A. Jawahery,⁶⁰ M. John,⁵⁷ D. Johnson,⁴⁰ C. R. Jones,⁴⁹ C. Joram,⁴⁰ B. Jost,⁴⁰ N. Jurik,⁶¹ S. Kandybei,⁴⁵ W. Kalso,⁶ M. Karacson,⁴⁰ J. M. Kariuki,⁴⁸ S. Karodia,⁵³ M. Kecke,¹² M. Kelsey,⁶¹ I. R. Kenyon,⁴⁷ M. Kenzie,⁴⁰ T. Ketel,⁴⁴ E. Khairullin,³⁵ B. Khanji,^{21,40,b} C. Khurewathanakul,⁴¹ T. Kim,⁹ S. Klaver,⁵⁶ K. Klimaszewski,²⁹ S. Koliiev,⁴⁶ M. Kolpin,¹² I. Komarov,⁴¹ R. F. Koopman,⁴⁴ P. Koppenburg,⁴³ A. Kozachuk,³³ M. Kozeiha,⁵ L. Kravchuk,³⁴ K. Kreplin,¹² M. Kreps,⁵⁰ P. Krokovny,^{36,d} F. Kruse,¹⁰ W. Krzemien,²⁹ W. Kucewicz,^{27,p} M. Kucharczyk,²⁷ V. Kudryavtsev,^{36,d} A. K. Kuonen,⁴¹ K. Kurek,²⁹ T. Kvaratskheliya,^{32,40} D. Lacarrere,⁴⁰ G. Lafferty,^{56,40} A. Lai,¹⁶ D. Lambert,⁵² G. Lanfranchi,¹⁹ C. Langenbruch,⁹ B. Langhans,⁴⁰ T. Latham,⁵⁰ C. Lazzeroni,⁴⁷ R. Le Gac,⁶ J. van Leerdam,⁴³ J.-P. Lees,⁴ A. Leflat,^{33,40} J. Lefrançois,⁷ R. Lefèvre,⁵ F. Lemaître,⁴⁰ E. Lemos Cid,³⁹ O. Leroy,⁶ T. Lesiak,²⁷ B. Leverington,¹² Y. Li,⁷ T. Likhomanenko,^{35,67} R. Lindner,⁴⁰ C. Linn,⁴⁰ F. Lionetto,⁴² B. Liu,¹⁶ X. Liu,³ D. Loh,⁵⁰ I. Longstaff,⁵³ J. H. Lopes,² D. Lucchesi,^{23,k} M. Lucio Martinez,³⁹ H. Luo,⁵² A. Lupato,²³ E. Luppi,^{17,a} O. Lupton,⁵⁷ A. Lusiani,²⁴ X. Lyu,⁶³ F. Machefert,⁷ F. Maciuc,³⁰ O. Maev,³¹ K. Maguire,⁵⁶ S. Malde,⁵⁷ A. Malinin,⁶⁷ T. Maltsev,³⁶ G. Manca,⁷ G. Mancinelli,⁶ P. Manning,⁶¹ J. Maratas,^{5,q} J. F. Marchand,⁴ U. Marconi,¹⁵ C. Marin Benito,³⁸ P. Marino,^{24,i} J. Marks,¹² G. Martellotti,²⁶ M. Martin,⁶ M. Martinelli,⁴¹ D. Martinez Santos,³⁹ F. Martinez Vidal,⁶⁸ D. Martins Tostes,² L. M. Massacrier,⁷ A. Massafferri,¹ R. Matev,⁴⁰ A. Mathad,⁵⁰ Z. Mathe,⁴⁰ C. Matteuzzi,²¹ A. Mauri,⁴² B. Maurin,⁴¹ A. Mazurov,⁴⁷ M. McCann,⁵⁵ J. McCarthy,⁴⁷ A. McNab,⁵⁶ R. McNulty,¹³ B. Meadows,⁵⁹ F. Meier,¹⁰ M. Meissner,¹² D. Melnychuk,²⁹ M. Merk,⁴³ A. Merli,^{22,n} E. Michielin,²³ D. A. Milanes,⁶⁵ M.-N. Minard,⁴ D. S. Mitzel,¹² A. Mogini,⁸ J. Molina Rodriguez,⁶² I. A. Monroy,⁶⁵ S. Monteil,⁵ M. Morandin,²³ P. Morawski,²⁸ A. Mordà,⁶ M. J. Morello,^{24,i} J. Moron,²⁸ A. B. Morris,⁵² R. Mountain,⁶¹ F. Muheim,⁵² M. Mulder,⁴³ M. Mussini,¹⁵ D. Müller,⁵⁶ J. Müller,¹⁰ K. Müller,⁴² V. Müller,¹⁰ P. Naik,⁴⁸ T. Nakada,⁴¹ R. Nandakumar,⁵¹ A. Nandi,⁵⁷ I. Nasteva,² M. Needham,⁵² N. Neri,²² S. Neubert,¹² N. Neufeld,⁴⁰ M. Neuner,¹² A. D. Nguyen,⁴¹ C. Nguyen-Mau,^{41,r} S. Nieswand,⁹ R. Niet,¹⁰ N. Nikitin,³³ T. Nikodem,¹² A. Novoselov,³⁷ D. P. O'Hanlon,⁵⁰ A. Oblakowska-Mucha,²⁸ V. Obraztsov,³⁷ S. Ogilvy,¹⁹ R. Oldeman,⁴⁹ C. J. G. Onderwater,⁶⁹ J. M. Otalora Goicochea,² A. Otto,⁴⁰ P. Owen,⁴² A. Oyangueren,⁶⁸ P. R. Pais,⁴¹ A. Palano,^{14,l} F. Palombo,^{22,n} M. Palutan,¹⁹ J. Panman,⁴⁰ A. Papanestis,⁵¹ M. Pappagallo,^{14,l} L. L. Pappalardo,^{17,a} W. Parker,⁶⁰ C. Parkes,⁵⁶ G. Passaleva,¹⁸ A. Pastore,^{14,l} G. D. Patel,⁵⁴ M. Patel,⁵⁵ C. Patrignani,^{15,f} A. Pearce,^{56,51} A. Pellegrino,⁴³ G. Penso,^{26,s} M. Pepe Altarelli,⁴⁰ S. Perazzini,⁴⁰ P. Perret,⁵ L. Pescatore,⁴⁷ K. Petridis,⁴⁸ A. Petrolini,^{20,h} A. Petrov,⁶⁷ M. Petruzzio,^{22,n} E. Picatoste Olloqui,³⁸ B. Pietrzyk,⁴ M. Pikies,²⁷ D. Pinci,²⁶ A. Pistone,²⁰ A. Piucci,¹² S. Playfer,⁵² M. Plo Casasus,³⁹ T. Poikela,⁴⁰ F. Polci,⁸ A. Poluektov,^{50,36} I. Polyakov,⁶¹ E. Polcarpo,² G. J. Pomery,⁴⁸ A. Popov,³⁷ D. Popov,^{11,40} B. Popovici,³⁰ C. Potterat,² E. Price,⁴⁸ J. D. Price,⁵⁴ J. Prisciandaro,³⁹ A. Pritchard,⁵⁴ C. Prouve,⁴⁸ V. Pugatch,⁴⁶ A. Puig Navarro,⁴¹ G. Punzi,^{24,t} W. Qian,⁵⁷ R. Quagliani,^{7,48} B. Rachwal,²⁷ J. H. Rademacker,⁴⁸ M. Rama,²⁴ M. Ramos Pernas,³⁹ M. S. Rangel,² I. Raniuk,⁴⁵ G. Raven,⁴⁴ F. Redi,⁵⁵ S. Reichert,¹⁰ A. C. dos Reis,¹ C. Remon Alepuz,⁶⁸ V. Renaudin,⁷ S. Ricciardi,⁵¹ S. Richards,⁴⁸ M. Rihl,⁴⁰ K. Rinnert,^{54,40} V. Rives Molina,³⁸ P. Robbe,^{7,40} A. B. Rodrigues,¹ E. Rodrigues,⁵⁹ J. A. Rodriguez Lopez,⁶⁵ P. Rodriguez Perez,⁵⁶ A. Rogozhnikov,³⁵ S. Roiser,⁴⁰ V. Romanovskiy,³⁷ A. Romero Vidal,³⁹ J. W. Ronayne,¹³ M. Rotondo,¹⁹ M. S. Rudolph,⁶¹ T. Ruf,⁴⁰ P. Ruiz Valls,⁶⁸ J. J. Saborido Silva,³⁹ E. Sadykhov,³² N. Sagidova,³¹ B. Saitta,^{16,j} V. Salustino Guimaraes,² C. Sanchez Mayordomo,⁶⁸ B. Sanmartin Sedes,³⁹ R. Santacesaria,²⁶ C. Santamarina Rios,³⁹ M. Santimaria,¹⁹ E. Santovetti,^{25,g} A. Sarti,^{19,s} C. Satriano,^{26,u} A. Satta,²⁵ D. M. Saunders,⁴⁸ D. Savrina,^{32,33} S. Schael,⁹ M. Schellenberg,¹⁰ M. Schiller,⁴⁰ H. Schindler,⁴⁰ M. Schlupp,¹⁰ M. Schmelling,¹¹ T. Schmelzer,¹⁰ B. Schmidt,⁴⁰ O. Schneider,⁴¹ A. Schopper,⁴⁰ K. Schubert,¹⁰ M. Schubiger,⁴¹ M.-H. Schune,⁷ R. Schwemmer,⁴⁰ B. Sciascia,¹⁹ A. Sciubba,^{26,s} A. Semennikov,³² A. Sergi,⁴⁷ N. Serra,⁴² J. Serrano,⁶

L. Sestini,²³ P. Seyfert,²¹ M. Shapkin,³⁷ I. Shapoval,^{17,45,a} Y. Shcheglov,³¹ T. Shears,⁵⁴ L. Shekhtman,^{36,d} V. Shevchenko,⁶⁷ A. Shires,¹⁰ B. G. Siddi,¹⁷ R. Silva Coutinho,⁴² L. Silva de Oliveira,² G. Simi,^{23,k} S. Simone,^{14,l} M. Sirendi,⁴⁹ N. Skidmore,⁴⁸ T. Skwarnicki,⁶¹ E. Smith,⁵⁵ I. T. Smith,⁵² J. Smith,⁴⁹ M. Smith,⁵⁶ H. Snoek,⁴³ M. D. Sokoloff,⁵⁹ F. J. P. Soler,⁵³ D. Souza,⁴⁸ B. Souza De Paula,² B. Spaan,¹⁰ P. Spradlin,⁵³ S. Sridharan,⁴⁰ F. Stagni,⁴⁰ M. Stahl,¹² S. Stahl,⁴⁰ P. Stefko,⁴¹ S. Stefkova,⁵⁵ O. Steinkamp,⁴² O. Stenyakin,³⁷ J. Stenzel Martins,² S. Stevenson,⁵⁷ S. Stoica,³⁰ S. Stone,⁶¹ B. Storaci,⁴² S. Stracka,^{24,t} M. Straticiuc,³⁰ U. Straumann,⁴² L. Sun,⁵⁹ W. Sutcliffe,⁵⁵ K. Swientek,²⁸ V. Syropoulos,⁴⁴ M. Szczekowski,²⁹ T. Szumlak,²⁸ S. T'Jampens,⁴ A. Tayduganov,⁶ T. Tekampe,¹⁰ M. Teklishyn,⁷ G. Tellarini,^{17,a} F. Teubert,⁴⁰ C. Thomas,⁵⁷ E. Thomas,⁴⁰ J. van Tilburg,⁴³ V. Tisserand,⁴ M. Tobin,⁴¹ S. Tolck,⁴⁹ L. Tomassetti,^{17,a} D. Tonelli,⁴⁰ S. Topp-Joergensen,⁵⁷ F. Toriello,⁶¹ E. Tournefier,⁴ S. Tourneur,⁴¹ K. Trabelsi,⁴¹ M. Traill,⁵³ M. T. Tran,⁴¹ M. Tresch,⁴² A. Trisovic,⁴⁰ A. Tsaregorodtsev,⁶ P. Tsopelas,⁴³ A. Tully,⁴⁹ N. Tuning,⁴³ A. Ukleja,²⁹ A. Ustyuzhanin,^{35,67} U. Uwer,¹² C. Vacca,^{16,40,j} V. Vagnoni,^{15,40} A. Valassi,⁴⁰ S. Valat,⁴⁰ G. Valenti,¹⁵ A. Vallier,⁷ R. Vazquez Gomez,¹⁹ P. Vazquez Regueiro,³⁹ S. Vecchi,¹⁷ M. van Veghel,⁴³ J. J. Velthuis,⁴⁸ M. Veltri,^{18,v} G. Veneziano,⁴¹ A. Venkateswaran,⁶¹ M. Vernet,⁵ M. Vesterinen,¹² B. Viaud,⁷ D. Vieira,¹ M. Vieites Diaz,³⁹ X. Vilasis-Cardona,^{38,e} V. Volkov,³³ A. Vollhardt,⁴² B. Voneki,⁴⁰ A. Vorobyev,³¹ V. Vorobyev,^{36,d} C. Voß,⁶⁶ J. A. de Vries,⁴³ C. Vázquez Sierra,³⁹ R. Waldi,⁶⁶ C. Wallace,⁵⁰ R. Wallace,¹³ J. Walsh,²⁴ J. Wang,⁶¹ D. R. Ward,⁴⁹ H. M. Wark,⁵⁴ N. K. Watson,⁴⁷ D. Websdale,⁵⁵ A. Weiden,⁴² M. Whitehead,⁴⁰ J. Wicht,⁵⁰ G. Wilkinson,^{57,40} M. Wilkinson,⁶¹ M. Williams,⁴⁰ M. P. Williams,⁴⁷ M. Williams,⁵⁸ T. Williams,⁴⁷ F. F. Wilson,⁵¹ J. Wimberley,⁶⁰ J. Wishahi,¹⁰ W. Wislicki,²⁹ M. Witek,²⁷ G. Wormser,⁷ S. A. Wotton,⁴⁹ K. Wraight,⁵³ S. Wright,⁴⁹ K. Wyllie,⁴⁰ Y. Xie,⁶⁴ Z. Xing,⁶¹ Z. Xu,⁴¹ Z. Yang,³ H. Yin,⁶⁴ J. Yu,⁶⁴ X. Yuan,^{36,d} O. Yushchenko,³⁷ M. Zangoli,¹⁵ K. A. Zarebski,⁴⁷ M. Zavertyaev,^{11,w} L. Zhang,³ Y. Zhang,⁷ Y. Zhang,⁶³ A. Zhelezov,¹² Y. Zheng,⁶³ A. Zhokhov,³² X. Zhu,³ V. Zhukov,⁹ and S. Zucchelli¹⁵

(LHCb Collaboration)

¹*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*²*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*³*Center for High Energy Physics, Tsinghua University, Beijing, China*⁴*LAPP, Université Savoie Mont-Blanc, CNRS/IN2P3, Annecy-Le-Vieux, France*⁵*Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France*⁶*CPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*⁷*LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France*⁸*LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France*⁹*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*¹⁰*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*¹¹*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*¹²*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*¹³*School of Physics, University College Dublin, Dublin, Ireland*¹⁴*Sezione INFN di Bari, Bari, Italy*¹⁵*Sezione INFN di Bologna, Bologna, Italy*¹⁶*Sezione INFN di Cagliari, Cagliari, Italy*¹⁷*Sezione INFN di Ferrara, Ferrara, Italy*¹⁸*Sezione INFN di Firenze, Firenze, Italy*¹⁹*Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy*²⁰*Sezione INFN di Genova, Genova, Italy*²¹*Sezione INFN di Milano Bicocca, Milano, Italy*²²*Sezione INFN di Milano, Milano, Italy*²³*Sezione INFN di Padova, Padova, Italy*²⁴*Sezione INFN di Pisa, Pisa, Italy*²⁵*Sezione INFN di Roma Tor Vergata, Roma, Italy*²⁶*Sezione INFN di Roma La Sapienza, Roma, Italy*²⁷*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*²⁸*AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*²⁹*National Center for Nuclear Research (NCBJ), Warsaw, Poland*³⁰*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*³¹*Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia*

- ³²*Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
³³*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
³⁴*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
³⁵*Yandex School of Data Analysis, Moscow, Russia*
³⁶*Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia*
³⁷*Institute for High Energy Physics (IHEP), Protvino, Russia*
³⁸*ICCUB, Universitat de Barcelona, Barcelona, Spain*
³⁹*Universidad de Santiago de Compostela, Santiago de Compostela, Spain*
⁴⁰*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
⁴¹*Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
⁴²*Physik-Institut, Universität Zürich, Zürich, Switzerland*
⁴³*Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands*
⁴⁴*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands*
⁴⁵*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
⁴⁶*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
⁴⁷*University of Birmingham, Birmingham, United Kingdom*
⁴⁸*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
⁴⁹*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
⁵⁰*Department of Physics, University of Warwick, Coventry, United Kingdom*
⁵¹*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
⁵²*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
⁵³*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
⁵⁴*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
⁵⁵*Imperial College London, London, United Kingdom*
⁵⁶*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
⁵⁷*Department of Physics, University of Oxford, Oxford, United Kingdom*
⁵⁸*Massachusetts Institute of Technology, Cambridge, MA, United States*
⁵⁹*University of Cincinnati, Cincinnati, OH, United States*
⁶⁰*University of Maryland, College Park, MD, United States*
⁶¹*Syracuse University, Syracuse, NY, United States*
⁶²*Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil (associated with Universidade Federal do Rio de Janeiro (UFRJ))*
⁶³*University of Chinese Academy of Sciences, Beijing, China (associated with Tsinghua University)*
⁶⁴*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China (associated with Tsinghua University)*
⁶⁵*Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia (associated with Université Pierre et Marie Curie)*
⁶⁶*Institut für Physik, Universität Rostock, Rostock, Germany (associated with Physikalisches Institut)*
⁶⁷*National Research Centre Kurchatov Institute, Moscow, Russia (associated with Institute of Theoretical and Experimental Physics (ITEP))*
⁶⁸*Instituto de Física Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain (associated with Universitat de Barcelona)*
⁶⁹*Van Swinderen Institute, University of Groningen, Groningen, The Netherlands (associated with Nikhef National Institute for Subatomic Physics)*

^aAlso at Università di Ferrara, Ferrara, Italy

^bAlso at Università di Milano Bicocca, Milano, Italy

^cAlso at Università di Modena e Reggio Emilia, Modena, Italy

^dAlso at Novosibirsk State University, Novosibirsk, Russia

^eAlso at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain

^fAlso at Università di Bologna, Bologna, Italy

^gAlso at Università di Roma Tor Vergata, Roma, Italy

^hAlso at Università di Genova, Genova, Italy

ⁱAlso at Scuola Normale Superiore, Pisa, Italy

^jAlso at Università di Cagliari, Cagliari, Italy

^kAlso at Università di Padova, Padova, Italy

^lAlso at Università di Bari, Bari, Italy

^mAlso at Laboratoire Leprince-Ringuet, Palaiseau, France

ⁿAlso at Università degli Studi di Milano, Milano, Italy

^oAlso at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil

^pAlso at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland

^qAlso at Iligan Institute of Technology (IIT), Iligan, Philippines

^rAlso at Hanoi University of Science, Hanoi, Viet Nam

^sAlso at Università di Roma La Sapienza, Roma, Italy

^tAlso at Università di Pisa, Pisa, Italy

^uAlso at Università della Basilicata, Potenza, Italy

^vAlso at Università di Urbino, Urbino, Italy

^wAlso at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia